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Aboveground hydrogen storage – Assessment of the potential market relevance in a Carbon-Neutral European energy system

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ABSTRACT

Hydrogen storage is expected to play a crucial role in the comprehensive defossilization of energy systems. In this context, the focus is typically on underground hydrogen storage (e.g., in salt caverns). However, aboveground storage, which is independent of geological conditions and might offer other technical advantages, could provide systemic benefits and, thereby, gain shares in the hydrogen storage market. Against this background, this paper examines the market relevance of aboveground compared to underground hydrogen storage. Using the open-source energy system model and optimization framework of Europe, PyPSA-Eur, the influence of geological independence, storage cost relations, and technical storage characteristics (i.e., efficiencies) on mentioned market relevance of aboveground hydrogen storage are investigated. Further, the expectable market relevance based on current cost projections for the future is assessed. The studies show that in terms of hydrogen capacities, aboveground hydrogen storage plays a considerably smaller role compared to underground hydrogen storage. Even when assuming comparatively low aboveground storage cost, it will not exceed 1.7% (1.9 $TWh_{H2,LHV}$) of total hydrogen storage capacities in a cost-optimal European energy system. Regarding the amounts of annually stored hydrogen, aboveground storage could play a larger role, reaching a maximum share of 32.5% (168 $TWh_{H2,LHV}$ a^{-1}) of total stored hydrogen throughout Europe. However, these shares are only achievable for low cost storage in particularly suited energy system supply configurations. For higher aboveground storage costs or lower efficiencies, shares drop below 10% sharply. The analysis identifies some especially influential factors for achieving higher market relevance. Besides storage costs, the demand-orientation of a particular aboveground storage system (e.g., hydrogen storage at demand pressure levels) plays an essential role in market relevance. Further, overall efficiency can be a beneficial factor. Still, current projections of future techno-economic characteristics show that aboveground hydrogen storage is too expensive or too inefficient compared to underground storage. Therefore, to achieve notable market relevance, rather drastic cost reductions beyond current expectations would be needed for all assessed aboveground hydrogen storage technologies.

1. Introduction

Hydrogen is considered an essential element in achieving fully renewable energy systems at optimal cost [1,2]. Besides its use as a feedstock in industry, hydrogen is being discussed as an option, e.g., for seasonal energy storage in power supply or the defossilization of parts of the transportation sector [3]. Such a broad introduction of hydrogen would require its widespread distribution and availability. To ensure this cost-effectively, the development of a hydrogen infrastructure (i.e., a pipeline system) is currently considered as a crucial and already pursued option [4]. Hydrogen storage is regarded as an indispensable component of such infrastructure for balancing temporal fluctuations in production and consumption.

Various storage options are currently being discussed for this purpose. While underground hydrogen storage (UGHS) in salt caverns is considered a promising low-cost option [5], other aboveground storage (AGHS) technologies are being investigated that enable hydrogen storage independent of geological conditions (e.g., pressure tanks, metal

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hydride storage [6], chemical storage [7], hydrogen carriers [8]). Due to often fundamentally higher (expected) cost for AGHS concepts [9], they generally perform worse in direct comparison with UGHS [10], e.g., in terms of levelized cost of storage. However, a comprehensive comparison requires a systemic perspective. This perspective should consider not only the hydrogen storage technology itself but also the impact that different storage characteristics have on the overall energy system, regarding, e.g., overall supply efficiency, necessary infrastructure development, and total system cost. Such an analysis focuses on the systemic value of different storage systems in an energy system context and derives the possible technology-specific market relevance from that (as proposed in [11] as an improvement of technology assessment solely based on levelized cost calculations). Here, especially the consideration of competing storage technologies allows for estimating under which conditions which storage system can achieve some market relevance and under which conditions it will be fully outperformed [12].

Several papers address the importance of energy storage – and hydrogen storage in particular – in future low-carbon energy systems. The importance of hydrogen storage as a component for energy systems with high shares of renewable energies is generally considered robust [13]. For reaching a low-carbon and highly renewable electricity system in Europe, energy (and hydrogen) storage plays an important role (being charged based on renewable energy supplying local demand) [14]. While sector coupling and cross-sectoral flexibilities can reduce the demand for energy storage, it remains important for achieving fully renewable energy systems [15]. Both aspects are also particularly true for large-scale hydrogen storage [16]. On a regional level, UGHS can be beneficial compared to other large-scale energy storage concepts. However, this depends on the level of defossilization and, thus, the overall importance of hydrogen [17]. While these studies focus on analyzing and evaluating the overall energy system, [11] provide a technology-focused evaluation and comparison of the systemic value and resulting market potential of different storage technologies. However, only a few different electrolyzer and fuel cell technologies (for hydrogen storage) and batteries are included in the assessment, primarily highlighting the methodological approach and the importance of considering systemic values for technology assessment. In [12], this approach is extended by a detailed comparison and evaluation of the potential market relevance of different competing storage concepts. Similarly, [18] explore the impact of cost and technical parameters (e.g., charge and discharge efficiencies) on the potential capacity deployment of new electricity storage systems. However, as in the other studies, only a single storage concept, i.e., compressed hydrogen storage, mainly underground, is considered for hydrogen. Therefore, this study attempts to close the identified research gap by conducting an in-depth analysis of the potential market relevance of different AGHS technologies through

- analyzing the influence of geological independence and storage costs (i.e., annual fixed costs) on the market shares of AGHS (and UGHS),
- comparing various AGHS concepts with different storage characteristics (e.g., round-trip efficiency) and assessing their cost-dependent market impact, and
- contributing to a general improvement in the understanding of the particularly influential factors for the market relevance of AGHS concepts.

For this purpose, the open-source energy system model and optimization framework PyPSA-Eur [4,19,20] is used to analyze the potential market relevance of different AGHS concepts compared to UGHS. The analysis focuses on the European energy system and Europe's potential future hydrogen storage requirements. Market relevance is evaluated by optimizing the system design and operation and calculating the impact of AGHS and UGHS in such a cost-optimized energy system. In this regard, both the potential for capacity expansion and the potential for contributing to the system operation, i.e., the amount of annually stored hydrogen, are assessed. So, market relevance is evaluated as the cost-optimal cumulated storage capacity and annually stored amount of hydrogen for a particular storage type.

In different case studies, first the market relevance of AGHS at different cost ratios to UGHS is investigated for idealized storage systems (i.e., 100% hydrogen storage efficiency). In this way, the value of independence from geological conditions offered by aboveground systems can be assessed. Subsequently, different hydrogen storage concepts are investigated by integrating suitable models into the PyPSA-Eur framework, particularly examining the influence of their technical characteristics on market relevance. Finally, the market relevance of different AGHS technologies is assessed for current estimates of techno-economic characteristics in the future.

2. Overall approach

Fig. 1 shows a flowchart of the implemented approach. Accordingly, the design and operation of the European energy system are optimized with respect to minimal annual system cost considering different system assumptions and case study specific aspects of aboveground (AGHS) and underground hydrogen storage (UGHS). The case studies include differences regarding the consideration of storage cost assumptions and the implementation of storage efficiencies (see section 3). Finally, the market relevance of AGHS and UGHS is evaluated concerning capacities and annual amounts of stored hydrogen (both with respect to the lower heating value (LHV) of hydrogen).

The following subsections give a more detailed overview of the different components of the overall approach, describing the utilized energy system model PyPSA-Eur, realized extensions regarding hydrogen storage as well as the evaluation criteria for calculating the market relevance.

2.1. Energy system model

The capacity expansion model PyPSA-Eur [4,19,20] is used to perform the discussed analyses. PyPSA-Eur is an open-source model and data set of the European energy system including the transmission network. It uses various openly available data sources to model energy demands throughout Europe's energy sectors (e.g., electricity, transport, heating, and industry). The countries of the European Union (EU27), as well as the United Kingdom, Norway, Switzerland, Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Serbia, and Kosovo, are included, while Cyprus and Malta are excluded [4]. In terms of energy infrastructure (i.e. electricity grid, gas grid), this European region is assumed to be isolated. Consequently, no energy flows across European borders are considered. However, an import of fossil fuels is implicitly taken into account by assuming unlimited availability in Europe. Fig. 2 shows an overview of the basic structure of PyPSA-Eur, regarding the included (energy) sources, infrastructure and storage, demand sectors, and necessary data inputs.

Both the temporal and the spatial distribution of energy demand and the potential of renewable energy supply in Europe are considered. Furthermore, intra-European energy flows between different regions are taken into account. Thus, PyPSA–Eur allows an assessment of system interrelationships under consideration of a spatiotemporal resolution (e.g., different regional potentials and varying temporal availability of renewable electricity generation, limited transmission capacities between geographic locations). Spatial resolution in particular sometimes requires pre-processing and regionalization of openly available data (e.g., local allocation of national energy demands based on spatially resolved information on population density). The corresponding processing steps are part of the workflow implemented in PyPSA-Eur. High-resolution regional data are then assigned to individual, regionally distinct nodes in the model. Energy infrastructure data are also adapted to these nodes representing the transportation capacities between the specific regions. In order to avoid excessive computational effort, the number of nodes is generally chosen not too high, resulting in a spatial

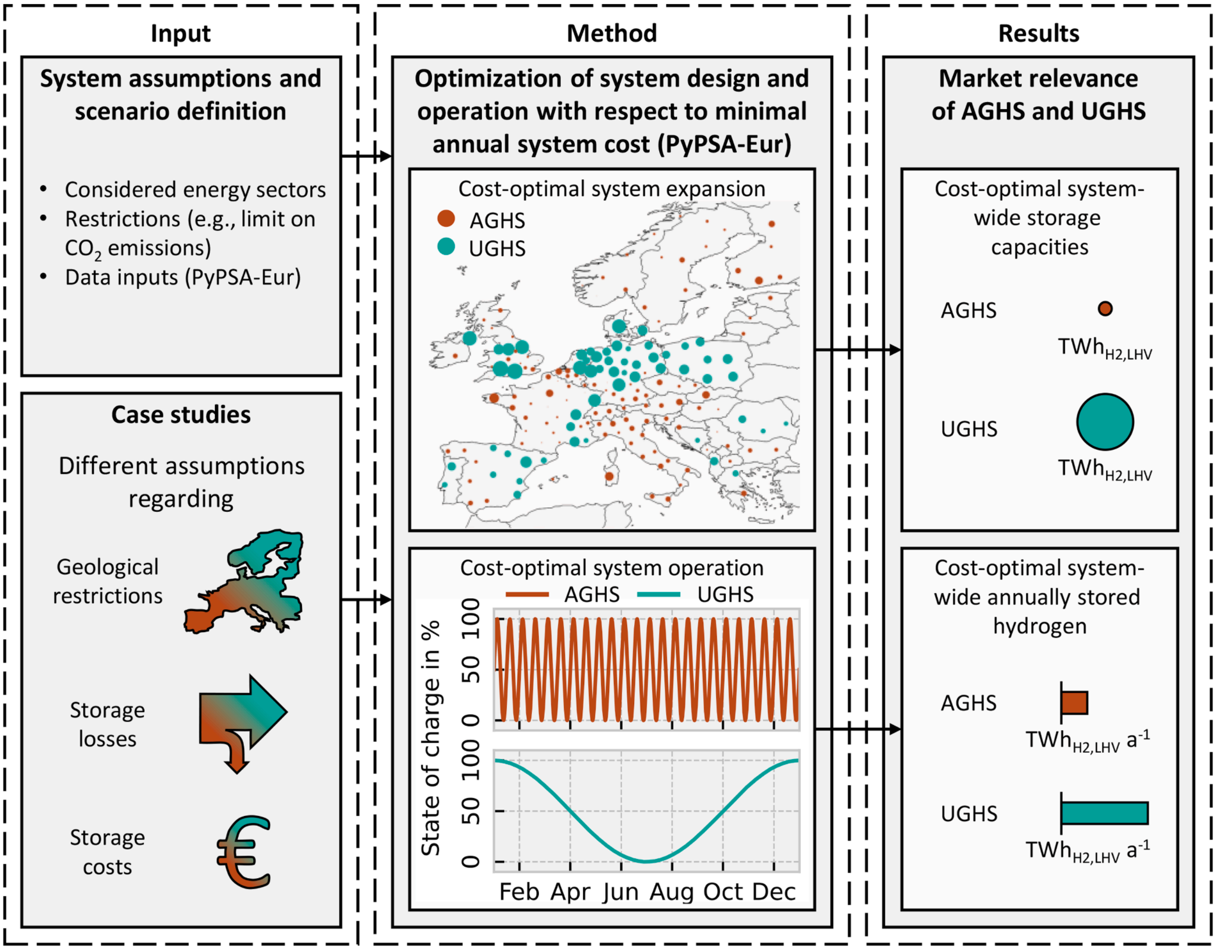


Fig. 1. Flowchart of the implemented approach. (AGHS: aboveground hydrogen storage, UGHS: underground hydrogen storage).

data-aggregation. Further, a temporal aggregation can be realized by combining several time steps. Subsequently, the aggregated energy system model is optimized by co-optimizing system design (i.e., capacity expansion) and operation. This involves optimizing the supply side, energy storage, possible energy conversion technologies, and energy transmission capacities. A linear optimization is performed to identify the system design and operation that would achieve minimum total annual costs (i.e., the sum of annualized investments and operational costs) while ensuring coverage of energy demand and taking into account potential further constraints (e.g., limited carbon dioxide emissions).

Regarding the system integration and storing of hydrogen, PyPSA-Eur includes data on existing natural gas infrastructure to account for pipeline repurposing potentials. It is assumed that when a pipeline is repurposed to transport hydrogen instead of natural gas, the energy flow (i.e., the pipeline capacity) is reduced (e.g., to 60% [4]), while the costs for repurposing are significantly lower than for the construction of an entirely new pipeline [21]. Where repurposing potentials are insufficient, the model endogenously allows the construction of dedicated hydrogen pipelines. Furthermore, a geographically resolved data set on the geological potential of underground hydrogen storage is included, which regionally limits or excludes the development of corresponding storage facilities. PyPSA-Eur is entirely open-source and freely accessible [22] (An overview of the mathematical formulation of the model can be found in Appendix A. Supplementary material).

2.2. Model extensions

PyPSA-Eur currently only implements hydrogen storage in underground salt caverns and aboveground pressure tanks directly connected to hydrogen production, consumption, and transportation. In order to be able to include different technical storage characteristics, the PyPSA-Eur model is extended by additional 'states' of hydrogen. The latter represent different pressure levels and absorption states (i.e., conversion to material-based hydrogen storage systems). Fig. 3 summarizes the model extensions graphically.

Specifically, this includes a lower pressure level, a medium pressure level, and a higher pressure level. The lower pressure level includes connections to electrolyzers, fuel cells, and hydrogen pipelines, representing a pressure level of roughly 30 to 60 bar [23]. The medium pressure level can be accessed by compressing hydrogen to 150 to 200 bar, representing the pressure level of UGHS in salt caverns [24]. Further compressing hydrogen to 350 to 400 bar leads to the highest considered pressure level, including AGHS in pressure tanks and the hydrogen demand in the mobility sector (assuming the supply of heavy-duty vehicles with a pressure level of 350 bar [25]). Conversely, lower pressure levels can be reached via individual expansion steps, e.g., if stored compressed hydrogen is to be used for power generation. It is assumed that this expansion neither requires nor provides any energy. Consequently, compression energy is lost when hydrogen is stored in compressed form and later used for electricity generation. Besides compressed gaseous storage, material-based hydrogen storage is considered. This is done by

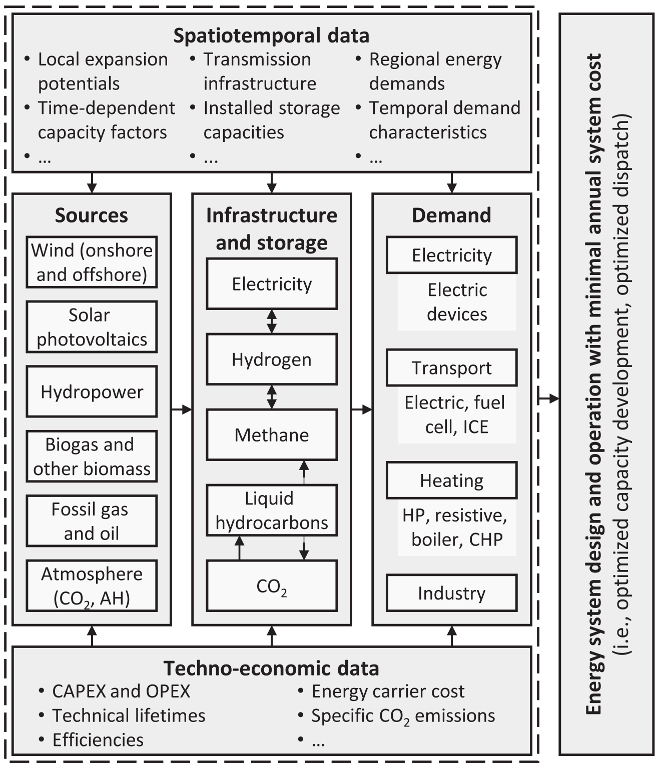


Fig. 2. PyPSA-Eur model structure (adapted from [4]) (CO_2: carbon dioxide, AH: ambient heat, ICE: internal combustion engine, HP: heat pump, CHP: combined heat and power).

including an absorbed state of hydrogen, which connects the lowest pressure level with various material-based storage types (e.g., metal hydride storage, liquid organic hydrogen carriers) via different absorber and desorber systems. Absorption and desorption generally result in a release or consumption of thermal energy. For fully sector-coupled studies in PyPSA-Eur, this energy supply and demand would result in a coupling to the heating sector. When excluding the heating sector, the necessary energy is supplied directly via electricity (i.e., resistive heater) or hydrogen (i.e., hydrogen burner).

The considered storage concepts allow a broad assessment of the influence of different storage characteristics (e.g., energy demand during charging versus energy demand during discharging) on the potential market relevance of AGHS; therefore, no further storage concepts (e.g., liquid hydrogen storage) are considered.

2.3. Assessment criteria

The assessment of market relevance addresses both the potential for capacity expansion MR_C (in $TWh_{H2,LHV}$) and the potential for actively contributing to the energy system's operation by storing hydrogen MR_E (in $TWh_{H2,LHV}\ a^{-1}$). The former is calculated according to equation (1) by adding the cost-optimal nodal storage capacities of the particular hydrogen storage technology $c_{store,n}$ across all nodes N of the optimized system configuration, which can be derived directly from the PyPSA-Eur optimization results.

$$MR_C = \sum\nolimits_{n=1}^{N} c_{store,n} \tag{1}$$

Thus, when discussing capacity-related market relevance, the total capacity installations of a particular hydrogen storage type across the entire cost-optimal European energy system are reported. The market relevance regarding stored amounts of hydrogen or energy MR_E is calculated accordingly. Here, according to equation (2), the discharged amounts of hydrogen $e_{store,n,t}$ per node n and time step t of the total amount of time steps T for the optimized system operation are added up, which are also direct results of the PyPSA-Eur optimization.

$$MR_E = \sum\nolimits_{n=1}^{N} \sum\nolimits_{t=1}^{T} e_{store,n,t} \tag{2}$$

Therefore, the market relevance related to system operation is reported as the cumulative annual amount of stored hydrogen in a particular storage type across the cost-optimal European energy system.

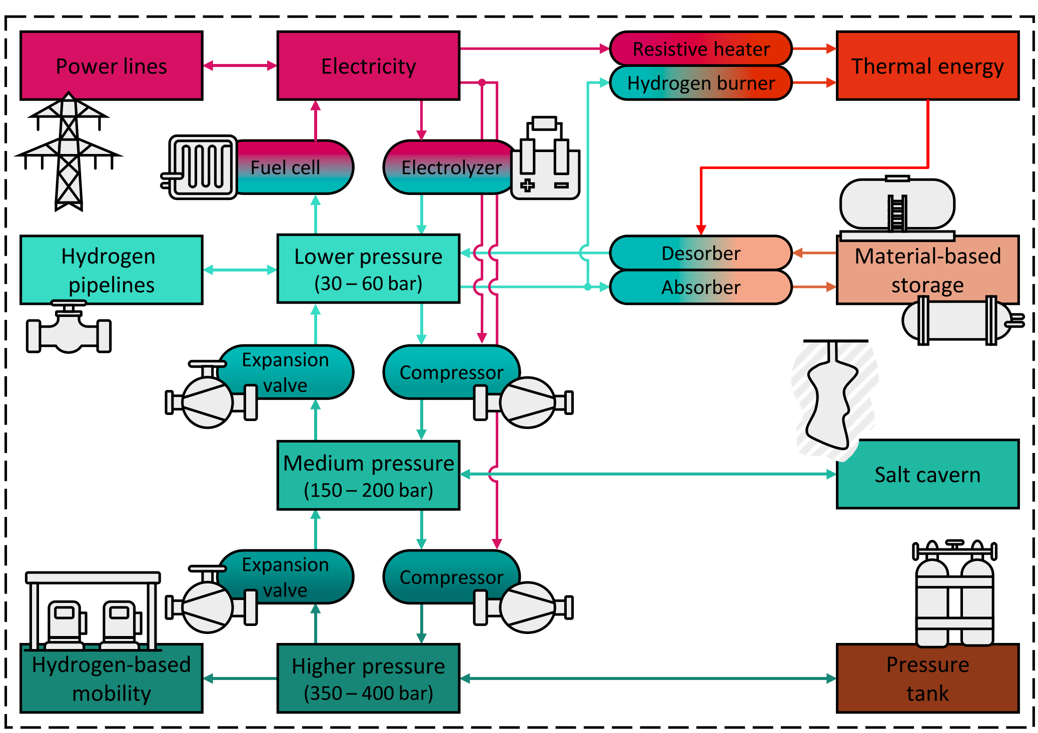


Fig. 3. PyPSA-Eur model extension by different hydrogen pressure levels as well as conditioning and storage systems.

3. System assumptions and case studies

The following sections give an overview of the general system assumptions, specific scenario definitions and the implemented case studies.

3.1. System assumptions

The scope of this study is limited to the electricity and land-based transportation or mobility sectors. As the goal is to analyze market relevance of aboveground (AGHS) and underground hydrogen storage (UGHS) in a potential future (greenhouse gas neutral) European energy system, the operational carbon dioxide emissions of the considered sectors are restricted to zero. Since an entirely domestic European energy supply is considered unlikely, incorporating further energy sectors (e.g., industry) would most probably be accompanied by the necessity to import hydrogen and its derivatives across European borders. As such imports are not modelled in PyPSA-Eur, the analysis is limited to a greenhouse gas neutral supply of the mobility sector, where hydrogen consumption would occur locally, and the electricity sector, where hydrogen could be used for seasonal energy storage. Consequently, both the influence of local hydrogen demands and the exclusive use of hydrogen as an energy storage option on the expansion and operation of AGHS and UGHS are considered. At this point, it should be noted that the analysis, thus, aims less at predicting the actual demand for hydrogen storage in Europe, but rather attempts to quantify the relative importance of AGHS and UGHS in meeting this demand.

For electricity generation, expendable solar photovoltaics, onshore wind, offshore wind, and existing hydropower are considered. Dispatchable power generation (e.g., geothermal, biomass, nuclear energy) is not considered. While it would generally be possible in the PyPSA-framework, PyPSA-Eur does not consider the inflexibilities of corresponding power plants (in particular cold-start times but also, e.g., ramp-up rates, minimum downtimes) due to the strong impact on computational complexity. Thus, including dispatchable power plants could lead to an underestimation of the (hydrogen) storage demand due to assuming power plants as too flexible. Therefore, such firm capacity is excluded. However, is it important to note that dispatchable power generation would generally reduce storage requirements, which would also affect the need for hydrogen storage (e.g., for seasonal balancing) [26,27]. Thus, the assessment in this paper represents an upper estimation of the market relevance of AGHS and UGHS in a cost-optimized European energy system.

Regarding spatial resolution, an aggregation to 181 nodes is realized (considered sufficient to adequately account for regional differences [28]). The analysis covers one year with a temporal resolution of 3 h, thus aggregating each 3 h-segment. The temporal aggregation serves the purpose of reducing the calculation complexity. However, it has the effect that temporal characteristics within the 3 h sections are no longer taken into account. As these are likely not dimensioning for hydrogen storage, this is considered uncritical for the investigated research question.

Expectations for the year 2035 are taken as the economic baseline for techno-economic data of the system components (e.g., system efficiencies, CAPEX, OPEX) [21], which corresponds to a point in time roughly between today and the (planned) achievement of greenhouse gas neutrality in Europe.

For energy transmission infrastructure development, a 125% limit on power line capacity expansion is assumed; i.e., transmission lines can be expanded by 25% in comparison to the already existing electricity transmission grid today. It should be noted that a lower or higher limit could have an increasing or decreasing effect on energy storage requirements. However, 125% is considered to be an appropriate assumption that allows the majority of cost benefits of grid expansion to be achieved [29], while at the same time implicitly reflecting existing acceptance problems. Retrofitting of natural gas pipelines for hydrogen transportation is based on the available pipeline system of today, assuming that hydrogen transportation can use 60% of current pipeline capacities. Besides repurposing, new dedicated hydrogen pipelines can be installed without further capacity restrictions.

PyPSA-Eur uses both ERA-5 [30] and SARAH-2 [31] for weather data. Here, data from 2013 are used, as the year represents a long-term average of both wind speed and solar radiation [32,33]. As a result, average values and not particularly high or low specific yields are assumed for electricity generation from renewable energies.

3.2. Scenario definition

For energy consumption in land-based transportation, two scenarios are assumed: Firstly, a comprehensive electrification scenario, where all final energy consumption for mobility is supplied directly via electricity, assuming that even long-haul truck traffic could be mostly electrified in the future [34]. Secondly, a scenario where 85% of useful energy consumption for transportation is covered by electricity and 15% by hydrogen (e.g., as fuel for heavy-duty vehicles). This second scenario results in an end energy hydrogen demand of the transportation sector of roughly 280 $TWh_{H2,LHV}$ a^1 (in the same order of magnitude as in [35]). Hydrogen-based transportation leads to an additional local hydrogen demand for refueling in the PyPSA-Eur model that follows the temporal characteristic of traffic volume published by the German Federal Highway Research Institute [36] (adapted to the local time) with a spatial distribution that is proportional to the nodal population. In both scenarios, electrified land-based vehicles are assumed to contribute to the energy system operation by performing vehicle-to-grid services, effectively leading to an exogenously defined increase in available battery storage capacity. Overall, the fundamental difference between the two scenarios is whether hydrogen is used solely to store electricity or whether there is a direct demand for hydrogen (in compressed form).

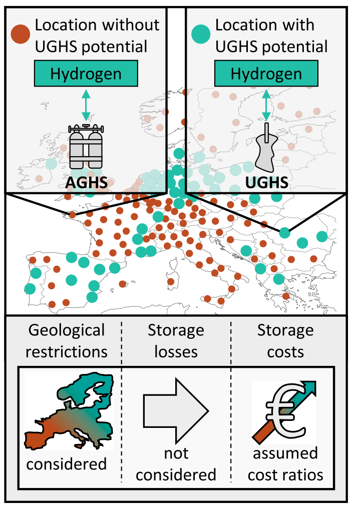
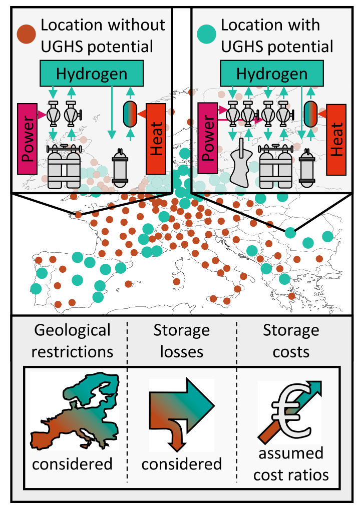
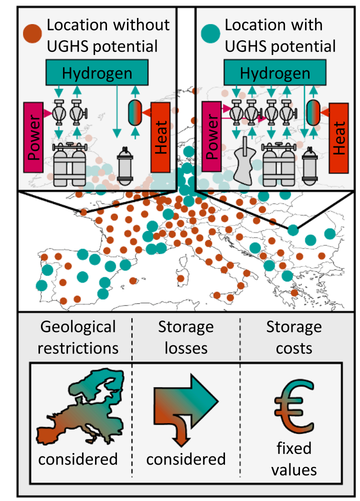
3.3. Case studies

This paper includes three case studies for the evaluation of the market relevance of AGHS and UGHS. Firstly, hydrogen storage is assumed to be idealized (i.e., lossless) and different cost ratios between AGHS and UGHS are considered in order to evaluate the isolated impact of geological independence and cost ratios on market relevance. Secondly, storage losses are included additionally to illustrate possible differences in the market relevance of different storage technologies. Finally, in the third case study, an analysis of the market relevance for current projections of techno-economic characteristics of AGHS and UGHS in the future (2035) is performed. Table 1 summarizes the differences between these cases and how they build on each other. The following sections further elaborate on the summarized aspects.

3.3.1. Case 1: Idealized lossless storage

First, an analysis of idealized AGHS and UGHS market relevance is carried out for various assumptions regarding their cost relations. The different storage categories are modeled as lossless hydrogen storages that can store and withdraw hydrogen at any time without technical restrictions, while hydrogen production and consumption still involve losses. The expansion of storage capacities is only restricted by the local potential for installing UGHS (i.e., geological conditions). Since the actual storage cost development is subject to great uncertainty, various assumptions are made here regarding the annual fixed costs of AGHS technologies. For this purpose, the ratio between the specific annual fixed costs (AFC) of AGHS and UGHS is introduced as a parameter of the case study. To evaluate the influence of specific storage costs on the cost-optimal expansion of AGHS and UGHS, different values are assumed for this this AFC-ratio φ_{AFC}, which is defined according to equation (3). *CAPEX* represents the specific investment costs, *OPEX* the relative fixed operational expenditures as a percentage of the specific investment and a the annuity factor. The indices represent aboveground (AGHS) and

Table 1
Summary of considered cases (AGHS: aboveground hydrogen storage, UGHS: underground hydrogen storage, CGH: compressed gaseous hydrogen, MH: metal hydrides, LOHC: liquid organic hydrogen carriers, DBT: dibenzyltoluene, MgH_2: magnesium hydride, $TiFeH_2$: titanium iron hydride, ex.: model exogenous desorption energy, end.: model endogenous desorption energy).

	Case 1: Idealized lossless storage	**Case 2**: Storage including conversion losses	**Case 3**: Expected techno-economic parameters
Graphical summary			
Research objective	Influence of the independence of geological conditions and storage cost relations on market relevance	(Additional) influence of different conversion and storing energy demands or losses on market relevance	Analysis of expectable market relevance for projected techno-economic parameters (in 2035)
Supply scenarios	• Land-based mobility 100% electrified (0% H2M) • Land-based mobility 85% electrified and 15% hydrogen-based (15% H2M)		
Storage costs	Assumption of different cost ratios between AGHS and UGHS		Fixed expected values (and assumed 50% cost reduction)
Hydrogen storage technologies	• UGHS: Idealized (lossless) • AGHS: Idealized (lossless)	• UGHS: CGH • AGHS: CGH, MH (ex. and end.), LOHC (ex. and end.)	• UGHS: CGH • AGHS: CGH, MgH_2 (end.), $TiFeH_2$ (ex.), DBT (end.)

underground hydrogen storage (UGHS).

$$\varphi_{AFC} = \frac{CAPEX_{AGHS}(a_{AGHS} + OPEX_{AGHS})}{CAPEX_{UGHS}(a_{UGHS} + OPEX_{UGHS})} \tag{3}$$

The annuity factor a is calculated according to equation (4). Here, $wacc$ is the imputed interest rate and l is the technical lifetime.

$$a = \frac{(1 + wacc)^l wacc}{(1 + wacc)^l - 1} \tag{4}$$

The imputed interest rate is set to 7% (as it is for all components in PyPSA-Eur [22]), while the technical lifetime is a technical characteristic of each specific hydrogen storage system.

The market relevance of AGHS and UGHS is evaluated for $\varphi_{AFC} \in \{1, 2, 4, 6, 9, 12\}$, i.e., AGHS is assumed to have the same cost up to twelve times the annual fixed cost of UGHS. The latter roughly represents the cost relation between UGHS and aboveground pressure tanks for the techno-economic data in 2035 [21]. Therefore, the assumed cost ratios allow for analyzing achievable market shares for further cost reductions of AGHS.

3.3.2. Case 2: Storage including conversion losses

The second part of the assessment involves storage-related conversion efficiencies of different hydrogen storage concepts, thus, emphasizing technical characteristics and their impact on the market relevance of the respective storage systems. Costs are still varied based on cost relations according to equation (3), however, only considering $\varphi_{AFC} \in \{2, 4, 6, 9, 12\}$.

As AGHS concepts, the storage of compressed gaseous hydrogen in pressure tanks and the material-based storage of hydrogen in metal hydrides and liquid organic hydrogen carriers are considered. These technologies have a wide range of different storage characteristics. While gaseous hydrogen storage requires (electric) energy for charging (i.e., compression), material-based hydrogen storage requires (thermal) energy for discharging. In addition, different efficiencies are considered. Overall, this results in different challenges for the energy system, allowing an assessment of the influence of such characteristics on the market relevance of AGHS.

Since storage cost are still based on the different assumed cost ratios, the AGHS concepts solely differ regarding energy loss or demand for charging and discharging. Simplified values are assumed for these demands (Table 2), solely pointing out the general influence of technical characteristics on potential market relevance. Accordingly, 2.5% of the energy content of the compressed hydrogen is required as electricity input during hydrogen compression between the lowest and medium as well as the medium and highest pressure levels. Desorption of metal hydrides requires 10% of the hydrogen energy in thermal energy, for liquid organic hydrogen carriers this value is 25%.

To assess the influence of desorption/dehydrogenation energy demands in more detail, two variations are considered for the material-based hydrogen storage concepts – desorption based on freely available 'excess heat' implemented as lossless desorption/dehydrogenation and the endogenously optimized supply of the required thermal energy by directly using electricity (i.e., resistive heater) or hydrogen (i.e., hydrogen burner). Since desorption and dehydrogenation do not need additional energy in the 'excess heat' case, the two technologies are subsumed as 'material-based hydrogen storage'.

3.3.3. Case 3: Expected techno-economic parameters

In the third case study, projected techno-economic parameters for hydrogen storage technologies in 2035 are considered in order to quantify the expectable market relevance of different AGHS (and UGHS) technologies, if the projected cost development is achieved.

Consequently, costs are now taken from literature to assess which technology has the greatest potential to achieve market relevance. For this purpose, system simulations are repeated considering the cost assumptions in Table 3. Furthermore, a variation with 50% reduced CAPEX and OPEX (both regarding storage and conditioning) is realized. For the material-based AGHS options, endogenous energy supply is assumed for the desorption of magnesium hydride (MgH_2) and dehydrogenation of dibenzyltoluene (DBT), as the thermal energy needs to be supplied at high temperatures [38,39], making an additional energy expenditure the most realistic case. In contrast, titanium iron hydride ($TiFeH_2$) is a low-temperature metal hydride [39]. Thus, desorption is assumed not to incur an additional system endogenous energy demand.

4. Results and discussion

The results of the different case studies are presented and discussed in the following.

4.1. Case 1: Idealized lossless storage

Case 1 aims to evaluate the market relevance of aboveground (AGHS) and underground hydrogen storage (UGHS) that solely stems from the independence of and dependence on geological conditions as well as storage cost relations. For this reason, Fig. 4 first shows cumulated values of annually stored energies (electricity and hydrogen) and total hydrogen pipeline capacities throughout the European energy system model. The quantities are evaluated for both mobility supply scenarios (i.e., comprehensive electrification, 0% H2M, and consideration of 15% hydrogen-based mobility, 15% H2M), and all assumed ratios of annual fixed costs (AFC-ratio) between AGHS and UGHS.

The hydrogen-related system design and operation depend clearly on the considered AFC-ratios. However, only minor variations are discernible for AFC-ratios of six and above. Regarding electricity storage, the system is mostly independent of the cost of AGHS. Throughout the considered ratios, roughly 234 $TWh_{el}\ a^{-1}$ (0% H2M) and 260 $TWh_{el}\ a^{-1}$ (15% H2M) of electricity are discharged annually from the different power storages. Solely for equal costs of AGHS and UGHS, the amount of stored electricity reduces by roughly 4 $TWh_{el}\ a^{-1}$ (mainly due to slightly reduced stationary battery capacities). Consequentially, AGHS has a rather limited impact on electricity storage. Conversely, it has a more decisive influence on hydrogen pipeline capacities. The latter are evaluated here as total $TWkm_{H2,LHV}$ in Europe (i.e., the cumulative product of the capacity and length of each pipeline). For an AFC-ratio of twelve, total pipeline capacities equate to 121.1 $TWkm_{H2,LHV}$ (0% H2M) and 135.7 $TWkm_{H2,LHV}$ (15% H2M), while they reduce to 89.3 $TWkm_{H2,LHV}$ (0% H2M) and 102.2 $TWkm_{H2,LHV}$ (15% H2M) for equally cheap AGHS and UGHS. At the same time, the total amounts of annually stored hydrogen strongly increase with lower AFC-ratios. If AGHS cost are twelve times higher than UGHS cost, stored hydrogen amounts are 486.6 $TWh_{H2,LHV}\ a^{-1}$ (0% H2M) and 491.5 $TWh_{H2,LHV}\ a^{-1}$ (15% H2M). Assuming equal cost for AGHS and UGHS annually stored amounts increase to 560 $TWh_{H2,LHV}\ a^{-1}$ (0% H2M) and 571.6 $TWh_{H2,LHV}\ a^{-1}$ (15% H2M).

Table 2
Assumed energy demands for charging and discharging of different hydrogen storage systems (rounded values based on [21,37,38]) (UG: underground, CGH: compressed gaseous hydrogen, AG: aboveground, MHS: metal hydride storage, LOHC: liquid organic hydrogen carriers).

Storage		UG CGH	AG CGH	MHS	LOHC
Charging electricity demand	$kWh_{el}\ kWh^{-1}_{H2,LHV}$	0.025	0.05	0.0	0.0
Discharging heat demand	$kWh_{th}\ kWh^{-1}_{H2,LHV}$	0.0	0.0	0.1	0.25

Table 3
Techno-economic parameters of different hydrogen storage and hydrogen conditioning systems in 2035 (UG: underground, AG: aboveground, CGH: compressed gaseous hydrogen, MgH_2: magnesium hydride, $TiFeH_2$: titanium iron hydride, DBT: dibenzyltoluene).

Storage		**UG CGH**	**AG CGH**	**MgH_2**	**$TiFeH_2$**	**DBT**[e]
$CAPEX_{Cap.}$	$€\ kWh^{-1}_{H2,LHV}$	1.75	12.23	3.37[c]	16.26[c]	2.54[f]
$OPEX_{Cap.,rel.}$	%	0	2	2[+]	2[+]	2[f]
Lifetime	a	100	20	20[+]	20[+]	20
Based on ref.		[21]	[21]	[6,39], own assumptions	[6,39], own assumptions	[21,38,40], own assumptions
Conditioning		**Compression / Expansion**	**Compression / Expansion**	**Absorption / Desorption**	**Absorption / Desorption**	**Hydrogenation / Dehydrogenation**
$CAPEX_{Cond.}$	$€\ kW^{-1}_{H2,LHV}$	80.17 / -[a]	120.25 / -[a]	-[d] / -[d]	-[d] / -[d]	221.8 / 469.91
$OPEX_{Cond.,rel.}$	%	4 / -[a]	4 / -[a]	-[d] / -[d]	-[d] / -[d]	3 / 4
Lifetime	a	20 / -[a]	20 / -[a]	-[d] / -[d]	-[d] / -[d]	20 / 20
Electricity demand	$kWh_{el}\ kWh^{-1}_{H2,LHV}$	0.042 / -[a]	0.063[b] / -[a]	0[+] / 0[+]	0[+] / 0[+]	0.011 / 0
Heat demand	$kWh_{th}\ kWh^{-1}_{H2,LHV}$	- / -	- / -	−0.301 / 0.301	−0.115 / 0.115	−0.273 / 0.273
H_2-loss	%	0.5 / 0[+]	0.75[b] / 0[+]	0[+] / 0[+]	0[+] / 0[+]	3 / 1
Marginal cost	$€\ MWh^{-1}_{H2,LHV}$	- / -	- / -	- / -	- / -	1.94 [g] / 1.94 [g]
Based on ref.		[21,40], own assumptions	[21,40], own assumptions	[21,39], own assumptions	[21,39], own assumptions	[21,40], own assumptions

[a] Expansion is significantly less expensive than compression; it is assumed to incur no additional cost or losses.
[b] Assuming stage-wise compression ratios derived from [40] for three stages to reach the considered high pressure level.
[c] Values are calculated based on material costs, shares of material costs on system cost in [39] and practical hydrogen capacities given in [6]. No specific year for cost assumptions is stated; material costs are assumed constant. There is little literature on total metal hydride system cost. However, these values are considered to be on the lower end of cost expectations.
[d] Heat transfer system and pressure vessel costs are included in the storage CAPEX (40% for MgH_2 and 15 to 20% for $TiFeH_2$) [39].
[e] Values taken directly from for [40] (2030); no further cost reductions are considered between 2030 and 2035.
[f] Combined values for dibenzyltoluene and storage tank. OPEX are applied for the combined value
[g] Marginal cost stem from 0.1% of losses of dibenzyltoluene per storage cycle.
[+] Own assumptions without further remarks

Fig. 5 shows the allocation of total annually stored hydrogen to AGHS and UGHS (bottom) as well as the resulting storage capacities (top) for the same scenario conditions as in Fig. 4. The share of AGHS of the total amount of annually stored hydrogen increases significantly but limited for AFC-ratios of twelve down to two. Stored hydrogen in AGHS equates to roughly 0 $TWh_{H2,LHV}\ a^{-1}$ (0% H2M) and 3.1 $TWh_{H2,LHV}\ a^{-1}$ (15% H2M) for an AFC-ratio of twelve and increases to around 17.9 $TWh_{H2,LHV}\ a^{-1}$ (0% H2M) and 46.2 $TWh_{H2,LHV}\ a^{-1}$ (15% H2M) for an AFC-ratio of two. At the same time, UGHS shares of stored hydrogen amounts only decrease slightly. Thus, storing hydrogen in AGHS competes not only with UGHS but also hydrogen transportation via pipelines. Lowering AFC-ratios from twelve to two reduces UGHS amounts by 1.6% (0% H2M) and 3% (15% H2M), while the total 'hydrogen storage market' grows by 2% (0% H2M) and 6% (15% H2M), to the detriment of the 'hydrogen transportation market'.

According to Fig. 5, UGHS and total capacities stay mostly constant throughout the AFC-ratios of two to twelve and equate to 114 $TWh_{H2,LHV}$ (0% H2M) and 109 $TWh_{H2,LHV}$ (15% H2M), while AGHS

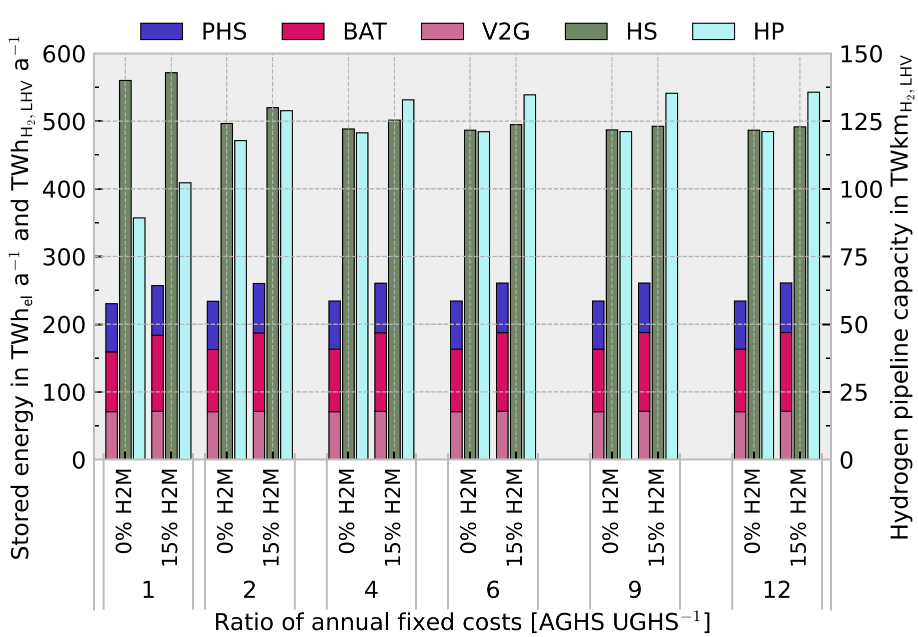


Fig. 4. Total annually stored energy (electricity and hydrogen) and hydrogen pipeline capacity for different ratios of annual fixed costs of aboveground and underground hydrogen storage (PHS: pumped hydro storage, BAT: stationary battery, V2G: vehicle-to-grid battery, HS: hydrogen storage, HP: hydrogen pipeline, H2M: hydrogen demand in mobility).

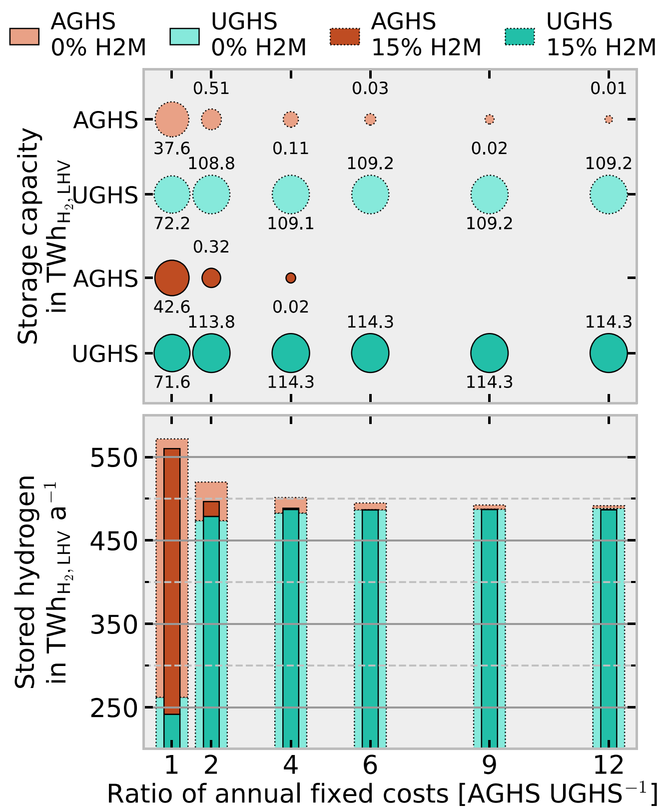


Fig. 5. Hydrogen storage capacity (top) and total annually stored hydrogen (bottom) for different ratios of annual fixed costs of aboveground (AGHS) and underground hydrogen storage (UGHS) (H2M: hydrogen demand in mobility).

capacities rise from roughly 0 $GWh_{H2,LHV}$ to 319 $GWh_{H2,LHV}$ (0% H2M) and 511 $GWh_{H2,LHV}$ (15% H2M). For the 'extreme' case of equal annual fixed costs of AGHS and UGHS, more than 50% of hydrogen amounts are stored in AGHS, while UGHS still achieves the more significant market relevance regarding capacities reaching roughly 62.7% (0% H2M) and 65.8% (15% H2M) of total hydrogen storage capacities. In contrast, expensive AGHS generally shows (almost) no contribution to an optimal system design and operation and, thus, would have no market relevance.

Hydrogen-based mobility has a significant impact on AGHS market relevance. If hydrogen only serves as a seasonal electricity storage, the market relevance of AGHS reduces rather quickly (i.e., at moderate cost differences to UGHS). However, when hydrogen-based mobility introduces local hydrogen demands, AGHS gains market relevance. The temporal fluctuations in hydrogen consumption require greater transportation capacity when supplied directly via pipelines than when local hydrogen storage helps to balance them. Thus, AGHS can more strongly contribute to an increase in pipeline utilization and a relative reduction in necessary pipeline capacities, if hydrogen is demanded locally (i.e., 2.8% (0% H2M) compared to 5% (15% H2M) pipeline capacity reduction between AFC-ratios of twelve and two). Consequently, some market relevance remains even for quite expensive AGHS if mobility is partly hydrogen-based.

Fig. 6 further emphasizes the differences between AGHS and UGHS market relevance by illustrating their role within the energy system. It shows which systems contribute to charging and which are supplied by discharging of AGHS (left) and UGHS (right). Since idealized AGHS and UGHS would generally perform the same system task if their costs are equal, Fig. 6 only includes the AFC-ratios from two to twelve.

When hydrogen is part of the final energy consumption in mobility, aboveground hydrogen predominantly discharges to supply mobility demands – especially locally. If comprehensive electrification is assumed, this energy amount is omitted. UGHS mainly supplies fuel cell operation (locally and externally via hydrogen pipelines). Hydrogen demand in mobility only plays a minor role. For completely electrified mobility, UGHS discharge for fuel cell operation increases roughly the same amount that hydrogen demand in mobility decreases. Generally, the charging of both storage types is performed by local electrolysis and – to a larger extent – by external electrolyzers and storage discharge at external nodes.

Overall, if annual fixed costs differ, AGHS market relevance is strongly coupled to a distributed local hydrogen consumption with corresponding demand variations, leading to an increased AGHS value through improving pipeline utilization. This is visible, as almost two-thirds of AGHS charging is achieved based on external hydrogen

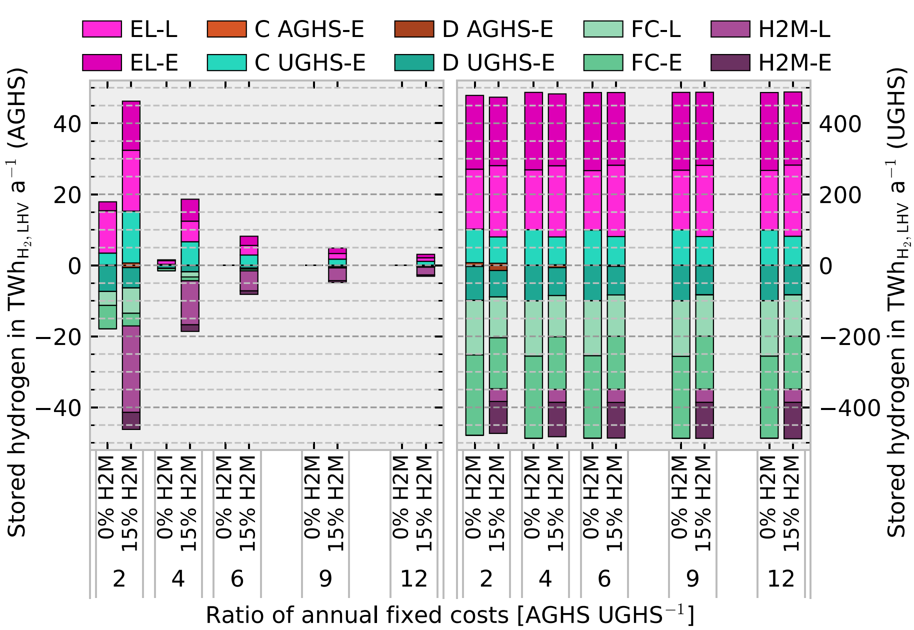


Fig. 6. Sources and destinations of hydrogen charging and discharging for aboveground (AGHS, left) and underground hydrogen storage (UGHS, right) for different ratios of annual fixed costs between AGHS and UGHS (EL: electrolyzer, C: charging from, D: discharging to, FC: fuel cell, H2M: hydrogen demand in mobility, L: local (node), E: external node).

supply, while roughly two-thirds of discharging supplies local hydrogen consumption (mainly in mobility). Consequently, without local hydrogen demands (or if their variations are balanced otherwise), AGHS does not play a role in the optimized system operation if its annual fixed cost exceed UGHS cost by four to six times.

4.2. Case 2: Storage including conversion losses

Having discussed the fundamental market relevance of aboveground (AGHS) and underground hydrogen storage (UGHS) that results exclusively from cost differences and geological conditions, the influences of technical differences will be examined in the following while still assuming different ratios of annual fixed costs (AFC-ratios). Metal hydrides and liquid organic hydrogen carriers are subsumed as 'material-based hydrogen storage' when desorption and dehydrogenation are assumed to operate based on freely available 'excess' heat. Consequentially, three distinct variations are considered for low pressure storage: Material-based storage with freely available 'excess' heat, metal hydride storage and liquid organic hydrogen carriers.

Fig. 7 shows the resulting storage capacities (top) and annual amounts of stored hydrogen (bottom) for different AGHS and UGHS implementations for different AFC-ratios. Again, both mobility supply scenarios (i.e., comprehensive electrification, 0% H2M, and 15% hydrogen-based mobility, 15% H2M) are considered. The plots show the idealized case (A), compressed gaseous hydrogen storage (B), material-based hydrogen storage (C), metal hydride storage (D), and liquid organic hydrogen carriers (D) from left to right. Compressed gaseous hydrogen storage (at medium pressures) is considered as the UGHS option in each non-idealized case.

The total amount of annually stored hydrogen is generally reduced by introducing further storage losses. This is least pronounced for the compressed gaseous hydrogen storage implementation (B), as (cheap) AGHS and UGHS together almost achieve the same amount of stored hydrogen as in the idealized case (A). However, at higher AFC-ratios total stored hydrogen amounts are generally roughly 100 to 125 $TWh_{H2,LHV}$ a^{-1} lower when including losses. Besides losses, the assumed AFC-ratio still strongly influences the amount of annually stored hydrogen. Further, the hydrogen demand in the mobility sector is important for total annual amounts of stored hydrogen.

Regarding AGHS technologies, it is quite apparent that mostly compressed gaseous storage (B) in the 15% H2M scenario and (lossless) material-based storage (C) of hydrogen play a more prominent role. At the same time, AGHS has almost no market relevance in the cases with metal hydrides (D) and liquid organic hydrogen carriers (E) with model endogenous energy supply for discharging. Overall, AGHS shares of total amounts of annually stored hydrogen reach maximum values of 3.6% (A), 1.9% (B), 13.7% (C), and around 0.3% (D) or 0% (E) for the 0% H2M-scenario. For 15% hydrogen-based mobility (15% H2M), these values amount to 8.9% (A), 32.5% (B), 19.6% (C), and around 1.5% (D) or 0.6% (E).

Total hydrogen storage capacities are mostly unaffected by the introduction of further hydrogen storage losses and are still mostly independent of assumed AFC-ratios. Total capacities are slightly below 110 $TWh_{H2,LHV}$ (0% H2M) and slightly above 114 $TWh_{H2,LHV}$ (15% H2M) for all implementations. The shares of AGHS capacities of these total values are far lower than for the amounts of stored hydrogen. For comprehensive electrification (i.e., 0% H2M), they reach maximum values of 0.3% (A), 0.2% (B), 0.4% (C), and slightly above 0% (D) or roughly 0% (E). For the 15% H2M scenario, these maximum values amount to 0.5% (A), 1.7% (B), 0.6% (C), and slightly above 0.2% (D) or roughly 0% (E).

Compressed gaseous storage is the most dominant implementation of AGHS technologies regarding installed capacities and annual throughput – provided hydrogen-based mobility is considered. Compression constitutes a necessity when supplying the mobility sector. High-pressure storage allows the energy demand for this compression to

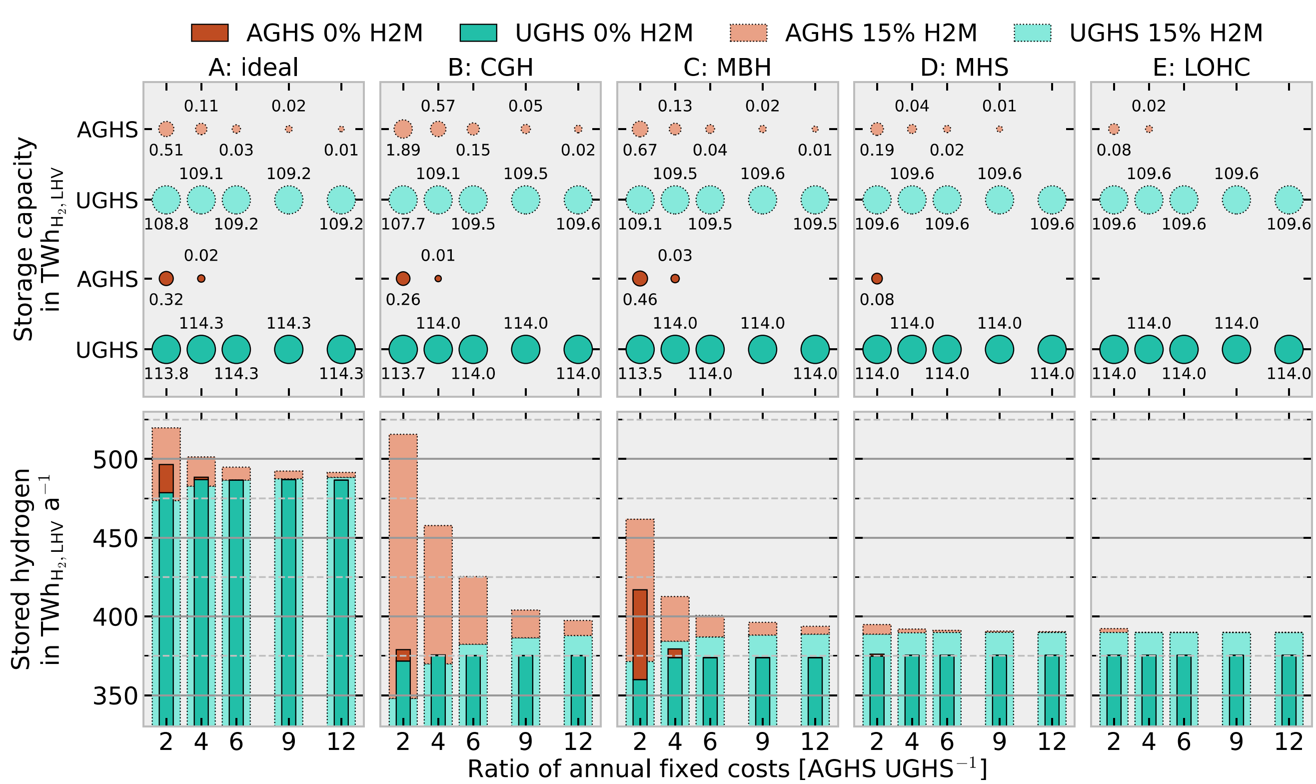


Fig. 7. Total storage capacities (top) and annually stored hydrogen (bottom) for different implementations of aboveground (AGHS) and underground hydrogen storages (UGHS) and different ratios of annual fixed costs. From left to right, the plots show idealized (lossless) hydrogen storage (A: ideal), compressed gaseous hydrogen (B: CGH), material-based hydrogen storage with freely available 'excess heat' (C: MBH), metal hydride storage (D: MHS) and liquid organic hydrogen carriers (E: LOHC). All non-idealized underground hydrogen storage is considered to be in compressed gaseous form (H2M: hydrogen demand in mobility).

be shifted to times when renewable electricity is abundant. Otherwise, compression would occur when hydrogen is consumed in the mobility sector, like in the case of material-based hydrogen storage. The latter shows the same total energy demand for supplying the mobility sector (i.e., an electricity demand equal to 5% of the hydrogen energy content). However, due to the temporal connection between compression and hydrogen demand in the mobility sector, flexibility is lost with respect to the timing of compression. This systemic drawback reduces the utilization and the implemented storage capacities of material-based compared to compressed gaseous hydrogen storage by roughly half. Thus, when hydrogen-based mobility is considered, increased flexibility regarding hydrogen compression favors compressed gaseous hydrogen storage out of all aboveground technologies. However, this systemic benefit is lost without hydrogen-based mobility, drastically reducing the value and market relevance of compressed gaseous AGHS.

In this scenario with full electrification of the mobility sector (0% H2M), material-based hydrogen storage with freely available energy for discharging achieves the highest market relevance out of all AGHS. Due to its efficiency advantage over UGHS in this case, it achieves even higher market relevance than for idealized AGHS and UGHS. Therefore, improving storage efficiencies beyond the UGHS efficiency can increase market relevance – provided storage cost are low enough. However, it is in no case certain that the assumed efficiency differences are actually achievable in reality (e.g., due to the possible unavailability of free 'excess' thermal energy in fully renewable energy systems).

The endogenous supply of desorption/dehydrogenation energy is systemically disadvantageous, as it generally coincides with an energy deficit in the system. Therefore, metal hydrides (D) and liquid organic hydrogen carriers (E) with endogenous supply of discharging energy would contribute insignificantly to the cost-optimal energy system and, thus, gain almost no market relevance even at low storage cost. This systemic disadvantage also partially explains the higher market relevance of AGHS in compressed gaseous form (B) compared to metal hydrides (D) or liquid organic hydrogen carriers (E) in the 0% H2M-scenario.

Fig. 8 further underlines the discussed differences in operational characteristics by showing which systems contribute to charging and which systems are supplied by discharging the different AGHS (top) and their underground counterpart (bottom) for an AFC-ratio of two. The strong impact of hydrogen-based mobility on the market relevance of AGHS is again visible – especially for compressed gaseous storage. The latter almost exclusively supplies local hydrogen demand in the mobility sector. Here, UGHS (local and external) contribute to charging compressed gaseous AGHS to a noticeable extent (roughly one-third) during times when cheap energy is available for compression, reducing UGHS's direct supply of the mobility sector. On the contrary, compressed gaseous AGHS contributes negligibly to supplying external nodes as this would negate the benefits of stockpiling high-pressure hydrogen. Material-based hydrogen storage contributes most significantly to the recharging of external storage compared to all other AGHS systems. The negligible contribution of metal hydride storage and liquid organic hydrogen carriers to a comprehensively electrified system operation (0%H2M) is apparent – the likewise small but comparatively more pronounced contribution from AGHS in compressed gaseous form is also discernible.

In summary, it can be stated that AGHS storage will likely only achieve some market relevance in a comprehensively defossilized electricity and mobility system if its annual fixed costs do not exceed UGHS costs substantially. Once costs for AGHS exceed underground storage costs by a factor of four to six, almost all impact on the 'hydrogen storage market' is lost. Furthermore, the system value of AGHS storage is strongly linked to the development of hydrogen-based mobility (or, more generally, local hydrogen consumption). Without local hydrogen demand (or if its variations were balanced out another way), AGHS strongly loses market relevance. Additionally, efficiencies play an essential role. If AGHS has efficiency benefits over UGHS, market relevance can be increased.

4.3. Case 3: Expected techno-economic parameters

Finally, the future expectable market relevance of different aboveground hydrogen storage (AGHS) technologies is discussed in comparison to UGHS in compressed gaseous form. For this purpose, Fig. 9 shows storage capacities and annually stored hydrogen of AGHS technologies, assuming

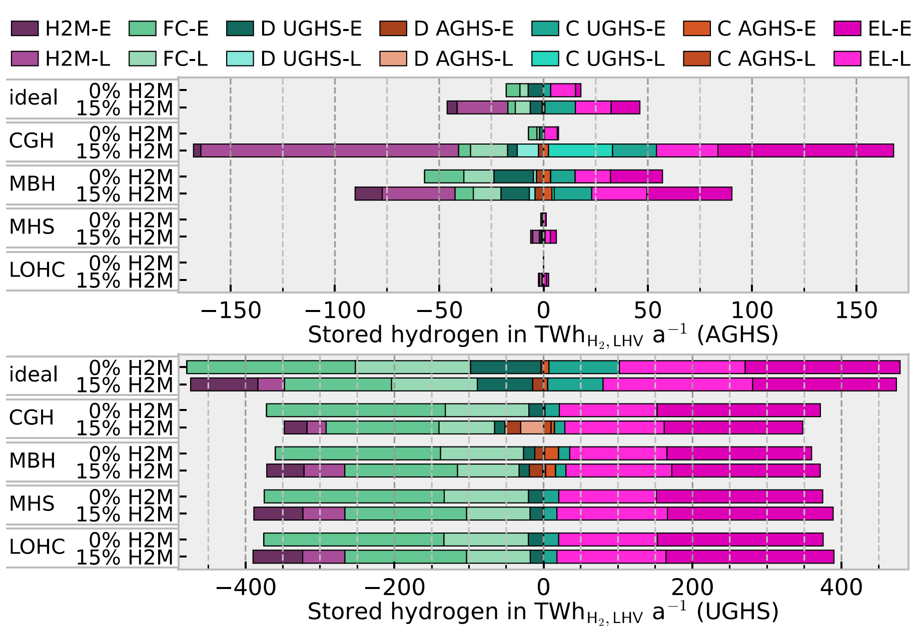


Fig. 8. Sources and destinations of hydrogen charging and discharging for different aboveground (AGHS, top) and underground hydrogen storage (UGHS, bottom) implementations for a ratio of annual fixed costs between AGHS and UGHS of two (H2M: hydrogen demand in mobility, FC: fuel cell, D: discharging to, C: charging from, EL: electrolyzer, E: external node, L: local (node), CGH: compressed gaseous hydrogen, MBH: material-based hydrogen storage, MHS: metal hydride storage, LOHC: liquid organic hydrogen carriers).

expected techno-economic parameters in 2035 and 50% reduced cost (i.e., CAPEX and OPEX of storage and conditioning technology), hence a stronger progression in AGHS development than expected nowadays. Both mobility scenarios (i.e., comprehensive electrification (top), 0% H2M, and 15% hydrogen-based mobility (bottom), 15% H2M) are considered.

Provided mobility will be partially hydrogen-based (bottom), compressed gaseous hydrogen could achieve the most significant market relevance regarding stored hydrogen amounts. In contrast, it would completely stop playing a role even at 50% of the expected cost in 2035 without local hydrogen demands (top). Regarding capacities, magnesium hydride would achieve the largest market shares relatively independent of the supply configuration in the mobility sector. However, an additional 50% cost reduction compared to the (already relatively low) values in Table 3 would be required to reach these capacities. Still, magnesium hydride is unlikely to play a larger role regarding stored hydrogen amounts, as the required high-temperature desorption heat results in poor overall hydrogen storage efficiencies. If lower temperature heat would be freely available for desorption (as assumed here), titanium iron hydride could play some role in the energy system operation. However, this would also depend on further reducing system cost by 50% (and thus, below the assumed material cost given today). Stationary storing hydrogen in dibenzyltoluene does not gain market relevance for the assumed techno-economic parameters, despite the relatively low cost regarding hydrogen storage capacities. Here, the high cost of hydrogenation and dehydrogenation plants play an important role, partially offsetting the storage capacity cost. Further, the required high-temperature energy for dehydrogenation results in low overall efficiencies. In addition, hydrogenation leads to 3% of hydrogen losses, causing higher necessary electrolyzer power inputs (i.e., an increase of roughly 4.3%) for the same amount of hydrogen being stored. Thus, the dibenzyltoluene option is already comparably inefficient in charging, while discharging is much less efficient than for other AGHS options as well as UGHS. If such aspects (i.e., hydrogen losses while charging and

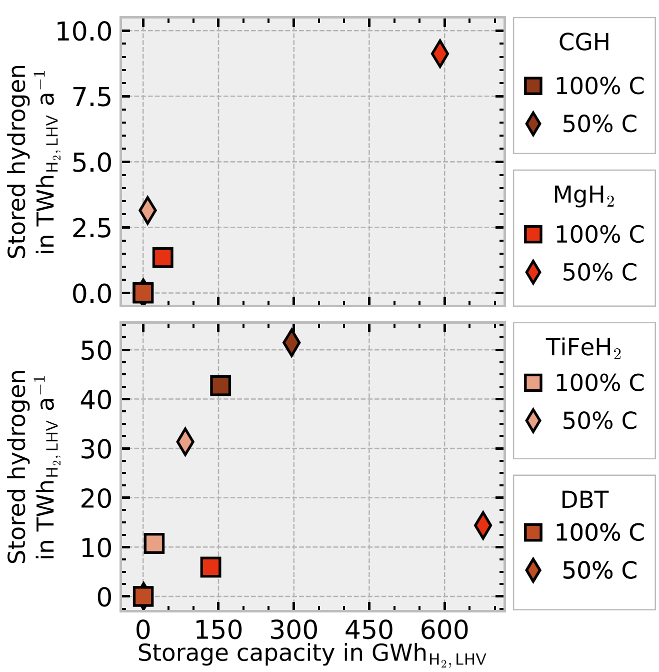


Fig. 9. Storage capacities and annually stored hydrogen for different implementations of aboveground hydrogen storage. Different shares of hydrogen in final energy consumption in mobility are considered; 0% (top) and 15% (bottom). Further, two cases with 100% and 50% of the expected CAPEX and OPEX in 2035 (C) are assumed. Dibenzyltoluene (DBT) and magnesium hydride (MgH_2) are dehydrogenated/desorbed based on model-endogenous energy and titanium iron hydride ($TiFeH_2$) is assumed to use 'excess' heat for desorption (CGH: compressed gaseous hydrogen).

discharging) were included for the two metal hydride options, their market relevance would also be lower.

Overall, compressed gaseous hydrogen is the only technology that could achieve noticeable market relevance regarding stored hydrogen amounts, even if only the expected cost in Table 3 are achieved. Here, 10% of operational market shares (i.e., shares of total stored hydrogen in AGHS and UGHS, which equate to around 350 TWh$_{H2,LHV}$ a^{-1} in all cases) could be exceeded. Capacity-wise, market shares would, however, not reach 0.2% of total hydrogen storage capacities (i.e., roughly 115 TWh$_{H2, LHV}$ in all cases). Further, this stands and falls with the hydrogen demand in transportation.

5. Summary and conclusion

This study investigates the potential market relevance of aboveground hydrogen storage (AGHS) compared to geologically dependent underground hydrogen storage (UGHS) in a fully defossilized cost-optimal European energy system, focusing on the electricity and mobility sectors. For this purpose, three case studies are evaluated, analyzing the isolated influence of geological independence and storage cost, the additional influence of storage efficiency, and finally, assessing the expectable market relevance of different AGHS systems based on their projected techno-economic characteristics in the future. Market relevance is evaluated as the cost-optimal cumulated storage capacity and annual amount of stored hydrogen for the particular storage type. The results of the case studies can be summarized as follows.

- The independence of geological conditions alone does not strongly favor AGHS over UGHS. Storage costs are a much more relevant factor. Assuming twice the annual fixed cost for AGHS compared to UGHS in an idealized, i.e., lossless case, the former would contribute roughly 0.3 to 0.5% to total hydrogen storage capacities and 3.6 to 8.9% to stored hydrogen amounts. For higher AGHS cost, market relevance declines sharply.
- Local hydrogen consumption, e.g., for hydrogen-based mobility, and its temporal variations can impact the market relevance of AGHS. Contributing to pipeline utilization increases the system value and, thus, the market relevance of AGHS. This impact is stronger regarding stored hydrogen (generally more than doubling the amounts) than regarding the potential for capacity expansion (an increase of at least 50%).
- Besides costs, efficiencies play a role in the market relevance of AGHS. If AGHS are more efficient than UGHS, they can take over some market shares. Between the cases of equally efficient UGHS and AGHS and more efficient AGHS, the relative shares of AGHS in storage capacity increase by at least 20% and the shares of stored hydrogen volumes more than double. However, as UGHS is already quite efficient, these potential benefits might hardly be achievable in reality.
- Systemic suitability (i.e., whether a storage and its operation are systemically beneficial) strongly impacts market relevance. While the temporally flexible charging of pressure tanks at consumption pressures increases its market relevance, the systemically disadvantageous energy demand for discharging metal hydrides and liquid organic hydrogen carriers negatively impacts their role in a cost-optimal energy system.
- Conversely, the energy system design also strongly influences AGHS market relevance. Assuming hydrogen demand in the mobility sector at pressure levels of AGHS in compressed form, the system value of corresponding storages increases drastically, contributing 1.7% to total hydrogen storage capacities and almost a third to total stored hydrogen amounts – however, sufficiently low AGHS system costs remain a crucial prerequisite for such large market shares. Further, if hydrogen is merely used for seasonal energy storage (i.e., 0% hydrogen-based mobility), the same aboveground systems reach only 0.2% of total capacities and 1.9% of total stored hydrogen amounts for the same storage cost assumptions.

- For the expected techno-economic data in 2035 none of the considered AGHS technologies is expected to achieve a substantial market relevance (less than 0.2% of total hydrogen storage capacities, and generally far lower than 15% of stored amounts). Merely above-ground compressed gaseous hydrogen storage could play a role, but only if mobility is hydrogen-based to some extent.
- All other technologies would require substantial cost reductions beyond what is currently expected to gain market relevance in the future.

While the assessed market relevance regarding capacities and stored hydrogen amounts for a cost-optimized European energy system does not directly reflect market relevance in reality, relations between AGHS and UGHS are still insightful. When assuming similar ratios between storage capacities and total consumption like for the current natural gas grid of roughly 25% [41] and projected hydrogen demands for 2050 (large span, e.g., 780 $TWh_{H2,LHV}$ [42] to 2 750 $TWh_{H2,LHV}$ [35]) the 'real world' hydrogen storage market would be larger. However, the relative market relevance of AGHS in this market still depends on the discussed influences and is likely limited. The consideration of further sectors might also influence hydrogen (storage) requirements. However, it is uncertain whether storage demand will be positively or negatively impacted. Although, higher hydrogen demands could imply an increased need for storing hydrogen, possible demand flexibility of different hydrogen consumers can reduce storage requirements even with higher total offtake [4]. The quantitative results should, therefore, be seen as a qualitative indication rather than a forecast of the market volume, while a categorical alteration of the statements made here about AGHS is not to be expected.

Thus, it can be concluded that the market relevance of AGHS technologies in stationary applications strongly depends on a drastic reduction of storage costs and favorable energy system configurations and would still be foreseeably limited. Given current expectations, further research should focus on reducing the AGHS cost to increase potential system values and, thus, market relevance.

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CRediT authorship contribution statement

Jelto Lange: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Michael Schulthoff:** Conceptualization, Methodology, Writing – review & editing. **Julián Puszkiel:** Conceptualization, Project administration, Writing – review & editing. **Lucas Sens:** Conceptualization, Writing – review & editing. **Julian Jepsen:** Funding acquisition, Project administration. **Thomas Klassen:** Funding acquisition, Project administration. **Martin Kaltschmitt:** Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118292.

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